Integrated"1 hermal Control for Mars Rover

Gregory S. Hickey, David Braun, Liang-Chi Wen, and Howard J. Eisen
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena CA 91109

Abstract

The Mars Rover has been built, environmentally tested and qualified for the 1996 launch far the Pathfinder mission to Mars. 1 he basic structure for the thermal control for the Mars Rover is the Warm Electronics Box (WEB). This consists of a thermal isolating composite structure with co-cured thermal control surfaces and an ultralightweight hydrophobic solid silica aerogel which minimizes conduction and radiation. 1 his design provides excellent thermal insulation at low gas pressures and meets the structural requirements for spacecraft launch loads and for a 60 g impact landing at Mars without damage to the insulation or structure. '1 he thermal design was a challenge due to the significantly diverse conditions during cruise and Mars surface operations, and restrictions placed on the Rover by the Pathfinder lander. 1 he thermal design includes three 1-Watt radioisotope heating units (RHU's), heaters on the batteries and the modem, which are inside the WEB, heaters on external motors, and a deliberate thermal heat leak to the Pathfinder lander structure during cruise through an attachment pin. The rover design has been thermally qualified in a series of both static and transient thermal-vacuum testing in vacuum and 8 torr pressure environments simulating all Mars and space cruise environmental conditions. Included was an 8 torr pressure test that simulated the expected wind conditions on the Mars surface. The Mars Rover has completed all environmental acceptance testing and is undergoing system integration testing with the Pathfinder lander.

Introduction

The Microrover Flight Experiment (MFEX) is part of the scientific and engineering payload for the Mars Pathfinder mission to explore the Martian surface. The Pathfinder mission is intended 10 provide an engineering demonstration of key technologies and concepts for the future exploration of Mars employing surface landers arid rovers. The mission is scheduled for launch in December 1996 on a Delta II expendable launch vehicle and is expected to land on Mars on July 4, 1997. Upon arrival at Mars, the pathfinder spacecraft will aerobrake through the Martian atmosphere protected by a heatshield, deploy a parachute, fire retrorockets, and land on airbags to dissipate the remaining entry velocity for a controlled landing on the Mars surface. The Mars Rover will then be deployed for its mission to explore the Mars surface. Its primary exploration phase is to be completed in 7 Martian days, with an extended mission goal of 30 days, A picture of the full rover system is shown in Figure 1. 1 his paper will discuss the integrated thermal design of the rover and the qualification testing in a simulated Martian surface environment.

The Mars rover is limited to a total mobile mass of 11 .0 kg, including the Alpha-Proton X-ray Spectrometer (APXS) scientific instrument, ten engineering experiment packages and an imaging system. The basic WEB structure is contained within a volume of 340 mm by 275 mm by 150 mm. I-he deployed rover size is 650 mm by 470 mm by 320 mm, It will have autonomous navigation, using a pair of wide angle imaging cameras for obstacle detection and avoidance. It's mobility will be provided by a six wheel drive, rocker-bogie suspension system. It will maintain two way contact with the Pathfinder lander via an ultra-high frequency (UHF) link with the lander. Power will be supplied from a single 0.20 m^2 GaAs solar panel that will provide a peak power of 16 Watts and a non-rechargeable battery system that can provide 150 W-hr at 50 % depth of discharge. The Mars Rover thermal subsystem consists of a Warm Electronics Box (WEB), three RHU heater units to provide a constant 2.9 Watts heat input, and various heater elements on the batteries, modem and actuators. The WEB must vent the air pressure during launch, survive launch and landing, and meet strict planetary protection standards. The WEB also has electrical cabling passing through the cable tunnel to connect with the solar array, motors, charge couple device (CCD) cameras, lasers, the drive system and other external experiments. The Mars Rover design developed from the need to meet conflicting thermal requirements, the need to stay within a system mass allocation without giving LJp functionality and the requirement to stay within a small volume envelope.

The overall thermal system requirements are based on the internal temperature requirements of the electronic components during the different phases of operation environments. "The Mars Rover utilizes standard industrial and military electronic components. Based on military specifications, the electronics are designed to operate in the range between +/-40°C. These limits are additionally constrained by the battery temperature requirements. The batteries are to be maintained at 40°C or less for the 3 months at the launch pad, 30°C for 8 months during cruise, and -30°C to 55°C (with less than 5 hours per day above 40°C) on the Mars surface.

The proposed landing site for the Pathfinder mission is a rocky plain in an area known today as Ares Vallis. "The site is 850 kilometers (527 miles) southeast of the location of Viking 1. ander 1, at a latitude of 15 degrees North. For this northern latitude and the planets location in its orbit, the mission will arrive in the equivalent of late spring 1 here will nominally be a 12.5 hr period of sunlight, with a peak solar insolation ranging from 475 to 550 W/m^2, depending on the atmospheric: opacity. The atmosphere is nominally 8 torr CO_2 gas, with average surface wind that may range from 0.2 to 1 m/sat night, and up to 4 m/s during the day. The expected diurnal surface and atmospheric temperatures are expected to range from a high of -23°C to a low of -83 'C. The diurnal thermal profile is shown in figure 2. The Mars Rover mission operation scenario is driven by the Martian environment and the power limitations on the Rover for heat generation. Primary internal heal is provided by the 2,9 W provided continuously by the RHU's. Power is provided by the solar array and is used internally for electronic: components, and externally for motor and steering drive mechanisms, for the lasers and cameras for navigation, and for the operation of the APXS. No battery power will he used to maintain internal temperatures as it is reserved for emergency surge and nighttime operations. The dissipated heat from the electronics provides the second significant source of internal heating during the day. There is a film heater' on the internal modem, to provide heating during early morning telecommunications. If needed, excess solar power can be shunted, via film heaters, to the batteries, which are the most significant thermal mass in the WEB and to the external actuators if early morning driving is necessary.

Thermal Design

The most significant thermal design features of the WEB arise not from the electronics range limitations while on Mars, but the that these temperatures must be maintained during the many different thermal environments on the Rover's journey to Mars

There are 5 distinct thermal environments in which the Rover must endure. They are ground operations before and after the integration of the RHU's; during cruise inside the Pathfinder lander; the first day on Mars when the Rover is still attached to the lander, and primary mission phase of the exploration phase on the Martian surface These five phases of operation drove the design and characteristics of the Mars Rover. Different mechanisms of heat transfer dominate during each of these five distinct thermal environments. On Earth, convection and conduction in a warm environment are the primary mechanisms to maintain the system within the temperature limits. The concern for ground handling operations is that the Rover batteries might become too warm in the interim prior to launch after the RHU's have been installed. This will be alleviated by special air conditioning during ground operations. During cruise, the thermal coupling to the relatively warm lander is nominally through radiation. There is no convection in the vacuum environment, and the launch attachments have a nonconductive link to the WEB. The Rover may become too hot due to the warm environment and poor thermal connectivity in the Pathfinder lander structure. '1 his drove the design for a conductive link from the Rover to the lander petal. The Pathfinder lander will t-rove an active cooling system to remove waste heat during cruise (1 ,2). 1 his is the primary thermal link of the Rover with the Lander. "1 here is no power or other direct electrical link with the Rover to the Lander. "1 his thermal link poses a potential problem for the first day on Mars, The Rover is expected to still be attached in its stowed position to the Lander for up to 24 hours after landing on Mars. In this configuration, the thermal link is still in place, and the linkage acts as a large thermal heat sink/convective fin prior to the Rover being released for its operations on the Martian Surface. This resulted in the first night on Mars to be the coldest conditions the Rover has to endure. On Mars at 8 torr atmospheric pressure, the wind from the CO_2 environment is still in the free continuum region and induces convective heat exchange. Heat is also exchanged through radiative transfer between the rover and deep space. These different environments and heat transfer mechanisms brought many challenges and concerns.

Mars provides a challenging thermal environment that is in a region of thermal transport that has not been well studied. It is also a regime which is not often encountered on terrestrial applications, and is very different from the vacuum environment all spacecraft encounter. '1 he 8 torr CO_2 environment falls in a transition regime between the continuum regime (50 torr and above) and the Knudsen free molecular conduction regime (1 torr and below). There has been a limited amount of evaluation of insulation materials for these environments. Wilbert, *et.al.* conducted a study for NASA's 1976 Viking lander that evaluated foam insulation, fibrous, powders and multilayer insulation (MLI) for thermal control (3). The result of that study was the primary use of several inches of foam insulation and some MLI on the Viking Landers. Other studies of thermal control in that time period assumed a foam insulation of 3 to 4 inches thick for potential Mars surface missions (4,5). A more recent study revisited the issue of Mars thermal control and evaluated additional porous fiber and particulate insulation(6). This bulky anti mass intensive approach for thermal control continued for the Pathfinder lander, which will use 2 inches of 5(I mg/cc foam enclosed in a composite honeycomb shell. All these systems or studies consider stationary landers and do not have tile mass and volume limitations that rovers do. Furthermore, larger landers have much more favorable thermal mass or volume to surface area ratio's, making thermal control much easier given the Martian diurnal cycle, In addition, stationary landers have the benefit of greater power generation through deployed solar array **panels.** The MFEX Rover was the first system to fully consider the unique physical constraints of the Martian environment. Early in the program various insulation concepts such as foams, fibrous insulation, vacuum jacketed enclosures, and opacified powders were studied before settling on the use of 15 to 20 mg/cc monolithic silica aerogel for thermal control. '1 he development and characterization of the aerogel design of the MFEX Warm Electronic Box (WEB) is discussed in Reference 7.

The use of aerogel for thermal control on Mars considers the thermal transport limitations for the transition between the continuum and free molecular regime. The effective thermal conductance of an insulative system consists of two components, the solid conductance-radiative component (independent of pressure) and the convective component. Gas conductance depends on the mobility inside the voids of a material, **and** is governed by the relative dimensions and connectivity of the open volume and the gas mean free path. If the interstitial space between material (whether they be voids, particles or fibers), becomes smaller than the mean free path of the gas within the insulation, the mechanism for gas transport shifts from the continuum regime to free molecular conduction in the Knudsen regime. ‘i he mean free path of a gas is inversely proportional to the gas pressure. I or CO_2 a! 10 torr, the mean free path is approximately 3 to 5 microns in the temperature range from - 90°C to 25°C. Solid aerogel has pore dimensions 6 to 11 nanometers. This means that the effective gas conduction within the aerogel is a fraction of value in the continuum regime, and is dominated by the conductive-radiative component of the silica aerogel structure. Since low density aerogels are 80 to 90% open cells, direct conductance is minimized. Because of the high void fraction and the resulting weak mechanical properties of low density aerogels, thermal control had to be designed and integrated into the lightweight supporting structure. This basic integrated structure and thermal insulation design became the basis for the WEB. The thermal conductivity of the aerogel integrated structure design is listed in “1 able 1.

This Mars rover utilizes a sheet and spar design for the WEB. This integrated structural and thermal design is composed of a set of E-glass/epoxy structural members, with each volume filled with low density solid silica aerogel insulation. The thickness and therefore strength of the facesheets and spars were varied with location on the WEB to optimize stiffness and reduce mass. Facesheets varied from 12 to 20 mil glass-epoxy, and were cocured with a film to provide the desired emissivity. “1 he exterior surface is covered with gold coated Kapton to provide a low emissivity surface to reduce radiation, and the interior is covered with Ni coated graphite to provider a high emissivity surface to equalize temperatures. The Ni-coated graphite also provides EMI protection. Nominal aerogel thickness is 25 mm for the side walls, and 32 mm for the bottom wall. The solar array consists of a honeycomb sandwich panel with a 32 mm thick glass-epoxy covered solid aerogel plug which fits into the top of the WEB. The honeycomb cells directly above the WEB are also filled with aerogel. Another design feature of the WEB is the cable tunnel. T he role of the cable tunnel seen at the front of the Rover in figure 1 is to provide additional thermal insulation for the cabling that must pass from the interior electronic to exterior components. Loss down the cables is decreased by a factor of 15 by providing insulation over a much longer length of the cable than would be obtained by a direct pass through, shifting the cable heat loss mechanism to copper conductance instead of conductance through the ‘1 eflon wire insulation, The insulation in the cable tunnel consists of Eccofoam polyurethane foam. The cable tunnel provides a 0.5 meter insulated path.

The solid silica aerogel performs as the main thermal insulation, with the thermal design tailored to minimize heat loss through the vertical spars. The silica aerogel was manufactured at the Jet Propulsion Laboratory (JPL) at a density of 15-20 mg/cc (0.94 -1 .25 lb/ft^3). To reduce internal radiation, a 5 mil gold coated kapton film was placed between the two layers of solid silica aerogel to act as a radiation barrier. The solid aerogel used in the Mars Rover is hydrophobic, and has good mechanical shock resistance. The open cavity sheet and spar design was dictated by the mechanical properties and handling ability of the aerogel. While the aerogel can mechanically withstand the loading from launch vibration and shock from the Mars surface landing when constrained within the walls, it is essentially a brittle-rubbery material at the low densities used in the Mars Rover. The material has good compressive properties, but low shear strength. "1 his necessitated that the WEB be built around the aerogel in a sequential manner. Fully assembled, the WEB has sufficient strength and stiffness to meet a 75 G launch and impact design requirement while supporting delicate internal electronics and external sensors,

One aspect of the small size and volume of the Mars Rover design is that interior components such as the structural axle tube span from side wall to side wall to provide mechanical stiffening. 1 he structural **axle** provides the mechanical attachment point for the rocker-bogie wheel assembly and transmits most of the WEB'S launch and landing structural loads, and houses the RHU's. It is designed out of glass-epoxy to meet structural requirements and minimize conductive losses. Attachments to the walls are through thermally isolating composite fittings. The design feature of directly attaching components to the walls was utilized to integrate the interior components with the structural design. The RHU's in the structural axial tube provide a constant heat source, Three sets of battery tubes are attached adjacent to this axial tube as shown in Figure 3. This provides a constant heating source to maintain the batteries within the specified temperatures when on the surface of Mars.

To prevent the overheating of the rover during cruise, a direct thermal link from the RHU's was incorporated into the thermal design. As illustrated in Figure 3, there is a direct conductive path from the structural axis tube to the Y-pin structural support. The path is via an aluminum clamp which is bonded to the structural axle tube with silver-filled epoxy and mechanically attached to the aluminum accelerometer tray. Coupled to the accelerometer tray is a copper braided strap which attached to a spring tensioned Y-pin. '1 he tensioning spring provides 10 lb. of contact force to mating surface. Thermal contact resistance is reduce by having Chotherm 11-79 between the Y- pin and the mating surface, This lander mounted surface **is** conductively coupled to the Lander active cooling loop (1) to dissipates approximately 2 watts continuously during the cruise stage of the mission. When the Rover arrives al Mars, it stands up on its rocker-bogie mobility system (6 to 30 hours after landing), and breaks the thermal contact with the lander cold finger.

The mobility system consists of six independently driven wheels and steering mechanism. In total, there are 10 independent motor assembles, six wheel motor drives and four steering motors on the exterior of the Rover. Though these motors can function at the cold temperatures on the Mars surface, their power requirement increases due to the increase in parasitic torque's as temperature decreases. The most power efficient concept for mobility to heat the motors to -20 to -40 °C via independent film heaters during operation. Heating to the motor assemblies and driving the rover account for 15°/0 and 8 % of the expected daily power utilization. This is an approximate value, since selection of the daily activities or I the surface is flexible. 1 here is also a motor drive mechanism on the APXS which has its own independent film heater. The cameras and laser assemblies operate at the ambient surface conditions.

Qualification Testing

The Mars Rover design has been extensively tested, both for its mechanical and thermal performance These tests were conducted at an engineering model level and at a flight System Integration Module (SIM) level and compared to the thermal model predictions. Reference 7 describes the engineering model testing and results, and provides a brief overview of the SINDA thermal model. The SIM qualification testing will be discussed here.

The objectives of the tests were to demonstrate Rover thermal design in keeping all components within critical operating and non-operating ranges in a realistic transient test environment 'I he SIM testing was also intended to demonstrate Rover functional performance and to qualify related components concurrently in the thermal conditions provided by the Pathfinder Rover in applied Martian nominal environments The Rover SIM Qualification testing was conducted in the 10' vertical thermal vacuum test chamber. The test hardware were mounted inside with a wind generator system placed on the chamber end-bell. 'This is illustrated in I igure 4. In addition to the chamber cold shroud there were three heat exchanger plates to simulate the ground (mounting plate), the solar/sky environment (sky plates) and a compensator plate to correct the gas temperature "I he Rover SIM unit was situated on the mounting plate. The Rover solar array, when deployed, was located about 12 inches underneath the sky plates, which consists of a copper (5'x3') and a stainless steel plate (5'x1') connected in series. During the initial phases the Rover, in the stowed mode, rested upon the Y-pin, which was connected to the fluid loop cold finger. To simulate Mars surface conditions, nitrogen at 8 torr was substituted for carbon dioxide. N_2 has a higher effective thermal conductivity in those conditions, but testing limitations with the chamber (such as icing) prevented the use of CO_2.

The wind generating system consists of a 30" fan, a 5-hp motor, a motor housing with a ferrofuildic feedthrough, a motor cooling system, a flow straightener and supporting structure. The front end (+X) of the SIM unit faced the fan. The two reference plates were suspended above the Rover solar array near the middle of the flow stream, (Gold reference plate in front). The Engineering Model of the Pathfinder Wind Sensor (ASI/MET was mounted in front of the Gold reference plate to monitor wind speed.

The SIM QUAL testing had two distinct phases: A) SIM-Q1, --wind calibration followed by a steady state thermal-vacuum testing representing the cruise stage near Mars before landing, (B) SIM-Q2, for a nominal transient operation (including the design conditions for wind, sky and solar) beginning with the Rover in the stowed position on the Lander petal for 24 hours before deployment , followed by 2 days of simulated ground operation. The test process was planned to be a simulation of the real flight operation starting at the landing on Mars at 3:00 AM. The test day was however', shortened to 24 earth-length hours (instead of 24.66 hours). Basically, the testing consisted of four independent but coordinated operations: (1) Rover functional operations which control the power dissipation at the Rover components (CPU/Power board, Modem, motor actuators, APXS electronic and current-limitor), (2) chamber and environmental heat exchangers, (3) wind generator and (4) RHU & Y-pin heaters and reference-plate heaters. The coordination of those activities were based on a pre-determined time-event schedule.

The second phase of the SIM testing evaluated the first day on Mars, followed by a simulated period of ground operation. During the test the Rover performed a number of pre-programmed tasks, including autonomous wakeup /shutdown and unstow. The wind apparatus was operational for the first 26 hrs of the test, then the motor drive mechanism failed. The effective wind near the reference plates was 1.0 m/s arid was nominally 0.6 m/s in the zone adjacent to the rover. These wind speed wore determined based on the calibration of the wind sensor. As expected the exterior components directly followed the simulated diurnal temperatures, figure 5 shows the internal temperatures for the RHU, the center of the axle tube arid the Y-pin fitting compared to the model predicted results. Figure 6 shows the temperatures for several of the interior electronic components compared to the model results. The modern was turned on for two separate intervals during this phase of the test. The impact of forced convection (due to wind) on the CPU temperature is approximately 3 degrees C in the stowed condition.

The next phase of the testing was after the rover stood up and simulated daily ground operations, Model and test results for the interior components are shown in Figure7. The CPU/Power board dissipated around 3.77 watts during most of the Rover operating periods between wake-up anti shut down. The small thermal masses cause these interior components (except the batteries) to follow the WEB interior temperature unless being heated separately. This is especially true for the modem. It responded very rapidly to heater power dissipation. However, once the external heating is removed, the modem temperature dropped rapidly and returned to a temperature level in equilibrium with the WEB interior, The effect of the wind is best illustrated by Figure 8, which shows the model results for the CPU board with and without the fan failure. The analytical predictions assume identical environmental conditions except the wind level. It can be seen that a steady wind of 0.6 m/s (at the Rover level) would shift the CPU temperature lower by about 7 to 8 degrees C. The effect of the wind is to produce internal thermal gradients which produce convective currents within the WEB.

Summary

The thermal design for small rovers for Mars exploration is a challenge due to mass, volume and power limitations. I-he design for the Mars rover meets this challenge by minimizing heat losses, providing for a continuous heat source with 2.9 W from RHU's and using low conductivity silica aerogel in an integrated structural design. Conflicting system requirements necessitate the integration of a thermal path to remove internal heat during the cruise mission phase, that becomes significant heat loss source during the initial landing operations. For surface operations, the thermal design is robust and meets all system requirements with significant margin. The Mars rover has been built and has completed all system level testing, and will be launched in December 1996 for operations on Mars in July 1997.

Acknowledgments

The work described in this paper was conducted at the Jet Propulsion Laboratory, California Institute of '1 echnology, under contract with the National Aeronautics and Space Administration

References

1. G. Birur, P. Bhandari, M. Gram, J. Durkee Howden, "integrated Pump Assembly - An Active Cooling System for Mars Pathfinder Thermal Control," SAE 26rd Int. Conference on Environmental Systems, Monterey CA, July 1996.
2. G. Birur, P. Bhandari, M. Gram, J. Durkee t lowden, "Mechanical Pumped Cooling Loop for Spacecraft Thermal Control," SAE 26rd Int. Conference on Environmental Systems, Monterey CA, July 1996.
3. O.J. Wilbers, B.J. Schelden, J.C. Conti, "Martian Soft 1. ander Insulation Study," Heat Transfer . and Spacecraft Thermal Control, Progress in Astronautics and Aeronautics, Vol. 24, pp. 630-658, Jan. 1970.
4. R. Nagel, "Thermal Control Aspects of a Stationary Martian Surface Laboratory," AIAA 3rd 'Thermophysics Conference, Los Angeles CA, June 1968.
5. T. Tracey, T. Morey," Mars Lander Thermal Control System Parametric Studies," AIAA 4th Thermophysics Conference, San Francisco CA, June 1969.
6. W. P. Fischer, W. Ebeling, B. Hass, K Keller, "Porous Insulation Performance under Mars Environment, " SAE 23rd Int. Conference on [environmental Systems, Colorado Springs CO, July 1993.

Table 1: Thermal Conductivity measurements of the Aerogel with Glass-epoxy structure at the coupon level.

Condition	Temperature (°C)	Thermal Conductivity (W/m-K))
1 atm	25	0.0333
10 torr CO_2	-79	00089
10 torr CO_2	-27	0.0126
10 torr CO_2	25	0.0163
1.2×10^{-3} torr Nitrogen	-78	0.0049
1.2×10^{-3} torr Nitrogen	-26	0.0074
0.4×10^{-3} torr Nitrogen	25	0.0113

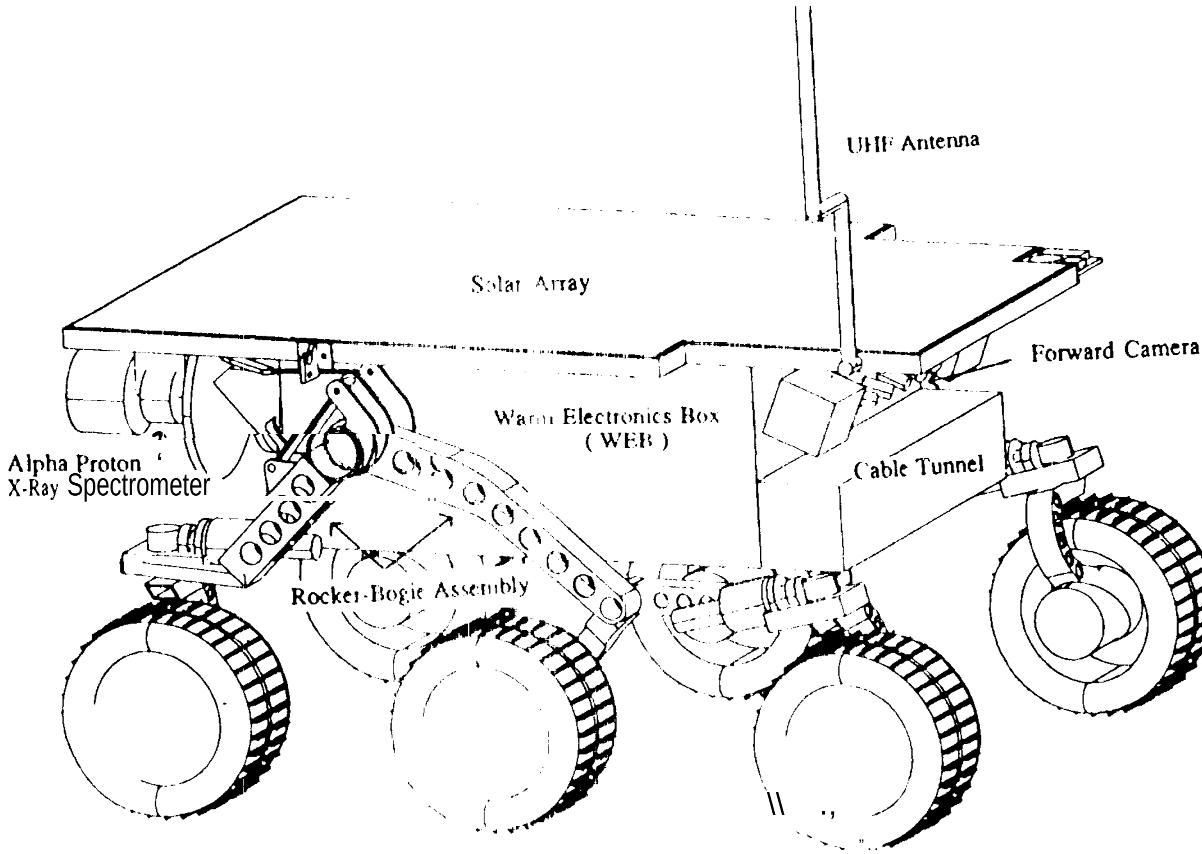

Figure 1, A picture of the full roversystem

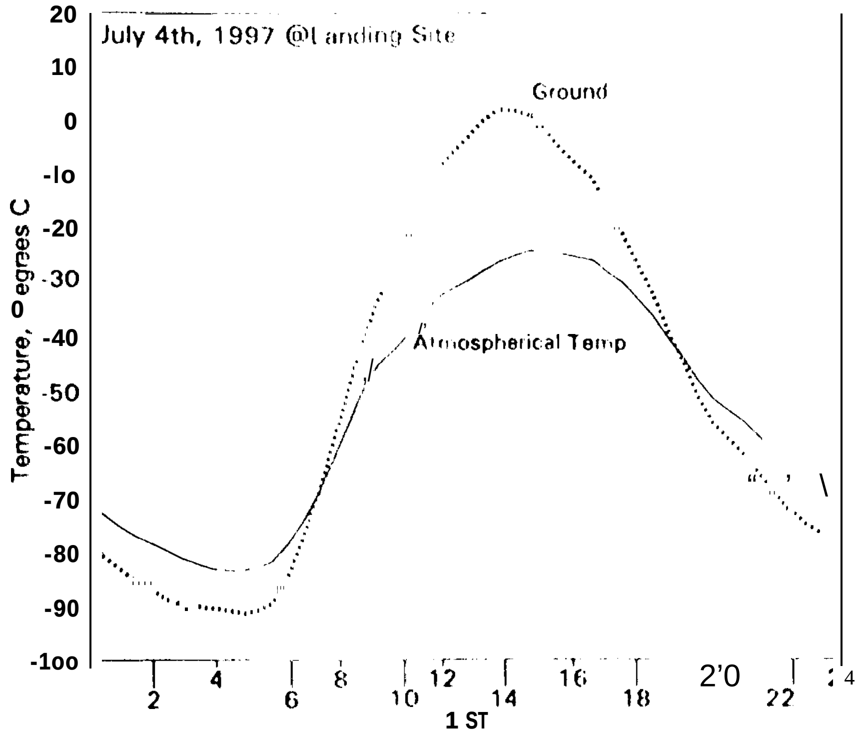

Figure 2. The diurnal thermal profile for the Mars landing site.

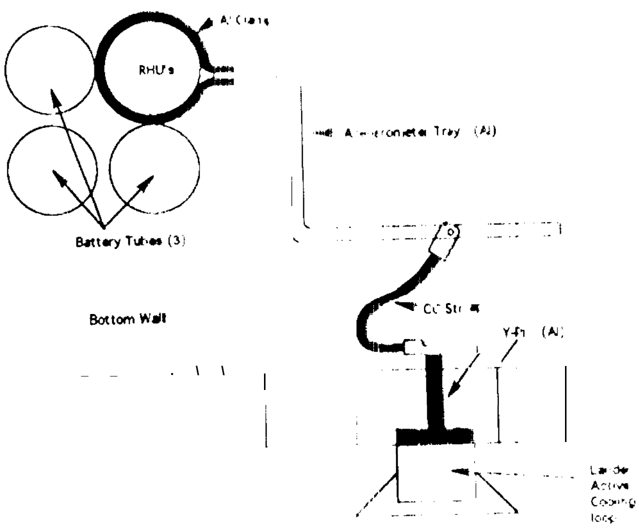

Figure 3: Schematic of the thermal path from the RHU's to the batteries and the Y axis attachment to the lander petal.

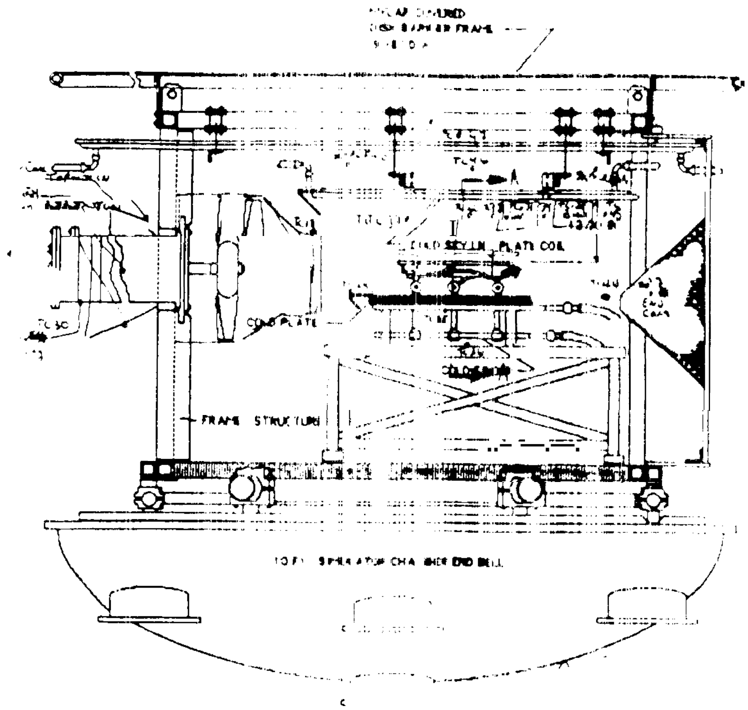

Figure 4: Test configuration for a the Mars rover in a simulated Mars Environment including surface winds

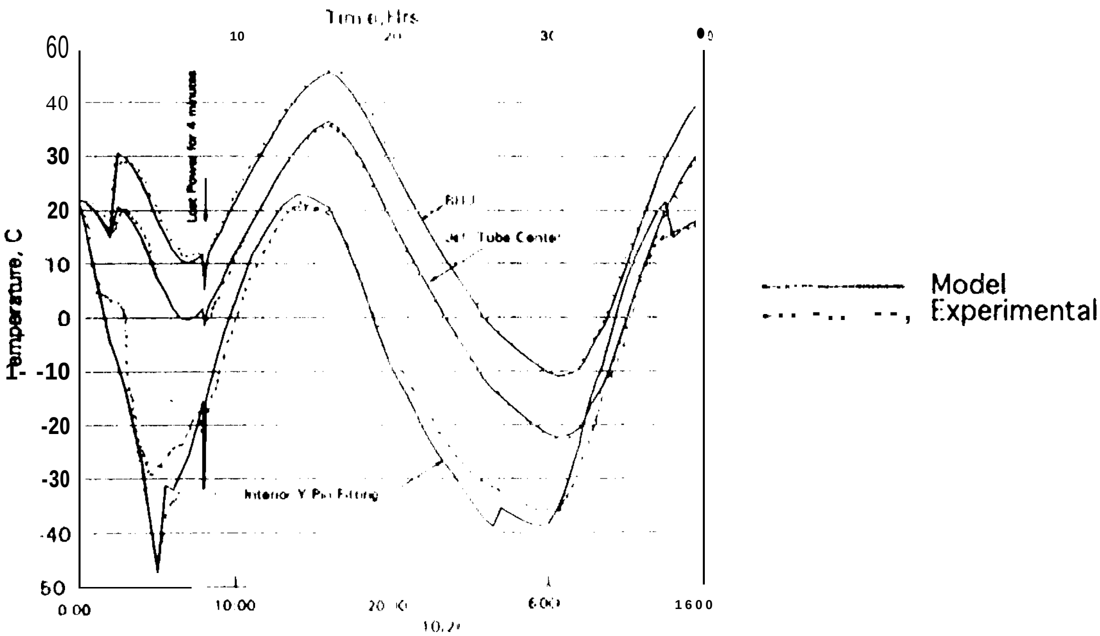

Figure 5 : Predicted and experimental temperatures for internal straps during the first day on Mars.

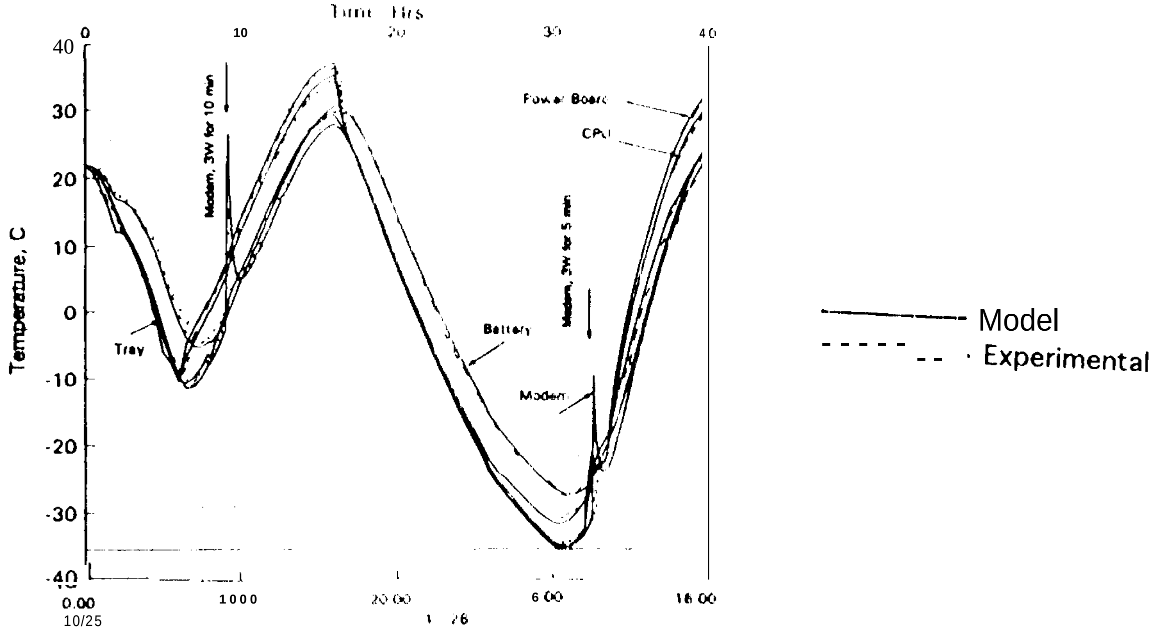

Figure 6 Predicted and experimental temperatures for interior components during the first day on Mars,

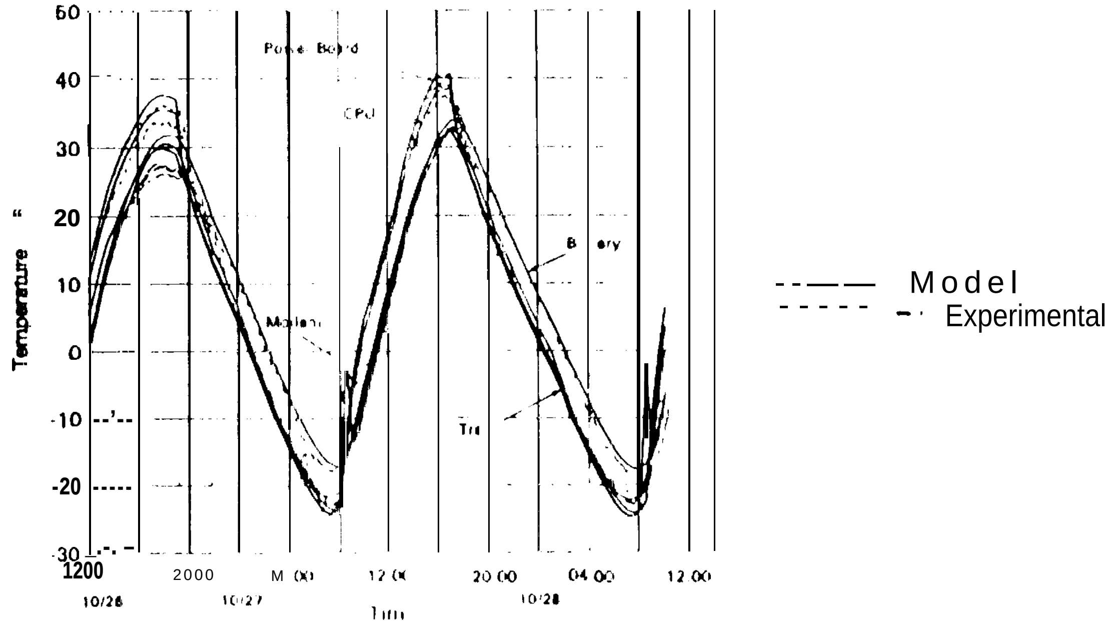

Figure 7 Predicted and experimental interior temperatures during the operational phase on the Mars surface.

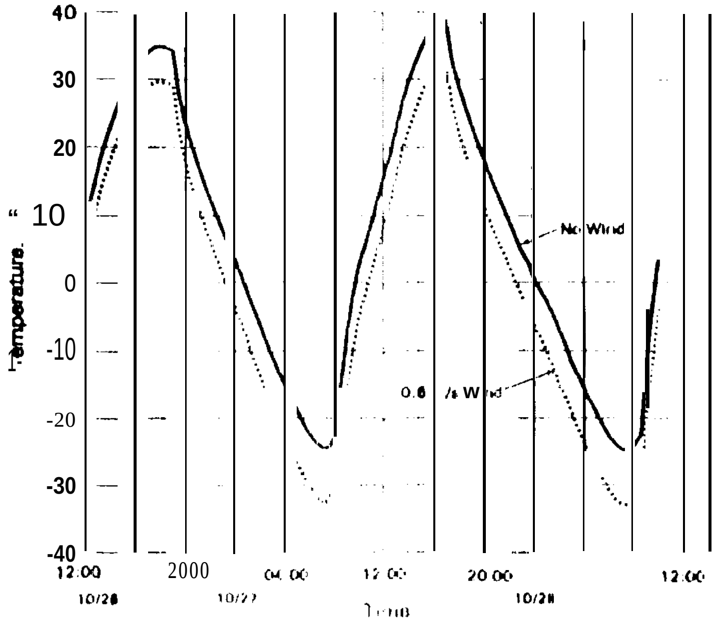

Figure 8 Effect of the Martian wind on the CPU board inside the warm electronics box.